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WIRELESS POWER TRANSFER - A TECHNOLOGY THAT HAS COME OF AGE

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ABSTRACT

Wireless power transfer has its roots in Tesla's experiments and his proposition that electric power can be transferred not only by means of radiation, but also by means of induction and resonant coupling. Recent trends in the development of this technology are addressed. Also the basic mathematical ideas that help us understand the various parameters and issues for optimization of power transfer are given. The power in a given load in case of two coils is compared with that obtained in a modified set up consisting of three coils and it is shown that by proper choice of coupling coefficients, one might improvise the existing methods.

Key words: Wireless Power Transfer (WPT), Maximum Power Transfer, Inductive Coupling, Relay Resonators

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1. INTRODUCTION

With the proliferation of cell-phones and various mobile devices that include even biomedical implants, the need for charging batteries and remote powering of electric circuits seems to grow increasingly. More than one hundred years ago, Tesla demonstrated [1, 2] wireless power transfer (WPT) through magnetic resonance and near-field coupling of resonant coupled circuits. Strictly speaking, even the induction machines, microwave heating and similar power devices are based on wireless power transfer. Since the distance between the source and the receiver is usually small in these cases, the prevailing connotation of the term "wireless" is not highlighted when we refer to them.

But over the past few decades, enormous work has been done and continues to be done in the field of WPT with the mobile devices and energy harvesters in mind. Also the coupling between the source and the receiver is understood to happen at a single frequency. More recently even multi-frequency multi-coil power transfer is being developed not only for short- range but also for mid-range applications. Broadly, WPT can be radiative or nonradiative depending on how the energy transfer is made to occur. In the case of radiative power transfer, we use a single antenna or an array of antennas that confine the energy in the form of a beam and propagate it through space over long distances. For transfer of energy from one point at the source to another point at the receiver this beam is supposed to be quite narrow and highly directed. Otherwise, the wave front of the radiating electromagnetic wave keeps spreading out as it travels and the power density decreases with distance and it is coupled to unwanted space. The second category of nonradiative wireless power transfer has its basis in the near-field magnetic coupling of coils with higher mutual inductance. Depending on power levels and the distances involved, this mechanism is further put into two sub-categories: short-range and mid-range transfer. The determining factor for this classification is the distance L between the source and the load and the maximum dimension D_{max} of the coil in which the energy is stored in the form of magnetic field. Suppose $L > D_{max}$, we classify the application as mid-range otherwise, it is a short-range power transfer. When $L \gg D_{max}$, it could be called long-range, but usually we come across such things not for power per se, but for message bearing signals; although, in space where losses are negligible long-range power transfer is possible. In all situations where the energy transfer is done via magnetically coupled coils, the analysis can be performed by using electric circuit theory [3, 4].

Going back in time, WPT has been employed in some biomedical applications since 1960s [5]. Even more recently Ho et al. [6] reported several medical advances in the design and implementation of micro-implants for deep-tissue placement. For heating applications WPT is used in induction ovens [7]. Even during the past two decades WPT principles have been extensively used for chargers meant for portable cordless devices such as cell phones [8]-[12]. Coming of age, WPT has inspired the formation of Wireless Power Consortium (WPC) [13], on December 17, 2008 now comprising about 135 companies worldwide. The WPC has undertaken to come up with a universal wireless power charging standard that allows electronic products and charging stations to be compatible with one another. Founding member companies include: Convenient Power Limited, Fulton Innovation LLC, Logitech SA, National Semiconductor Corporation, Royal Philips Electronics N.V., Sanyo Electric Co. Ltd., Shenzhen Sang Fei Consumer Communications Co. Ltd. and Texas Instruments Incorporated. Presently WPC has launched the “Qi” standard for portable electronic devices as it reached a stage of commercialization. Qi is an interface standard for inductive power transfer over distances of up to 4 cm. A typical system consists of a power transmission pad and a compatible receiver in the cellular phone or the mobile device that is placed over and above the transmission pad while electrical charging occurs through inductive coupling. According to Qi specification, power below 5 W is considered to be low. Through a feedback mechanism via backscatter modulation, the power receiver sends signals back to the transmitter indicating state of charge (SoC) of the battery, thereby the transmitter is made to function in an optimal way. In backscatter modulation the quality factor of the power-receiver coil is decreased causing changes in the charging current drawn from the power transmitter. These changes are demodulated and detected to yield the message needed for the two devices to work together. High power specifications from WPC up to 1 kW are

underway. Similar to Wi-Fi hotspots, Qi counter parts are expected to permeate the market places and every public corner. Charging base stations typically have a flat surface, referred to as the interface surface on top of which, a user can lay one or more mobile devices. The design of the surfaces could vary depending on how one is permitted to place the device. In guided positioning, the device has to be oriented in a specified manner that permits maximum energy coupling. In free positioning, there is no stringent requirement as to how one should place the device. The technique employing multiple cooperative flux generators [13] permits arbitrary orientation of the device within the prescribed area for charging the device. There is an excellent collection of papers on the topic of WPT and Qi standards, for example the reader is encouraged to see [14]-[17]. In fact, the present paper is inspired by these useful resources.

This paper is quite basic and is organized as follows: We first revisit the idea of maximum power transfer (MPT), the quantity η_T that shows maximum relative power and distinguish the same from maximum efficiency η_E of system performance as relevant to power communities. We find that these two objectives are mutually contradictory. This is done in case of a simple DC circuit just for the purpose of illustration. Then we give the Kirchhoff's equations for a system of N-coils and specialize the same for N = 2 and N = 3. Although it seems simple and straightforward, the analysis opens several issues that have not been addressed for a global optimization of maximum power transfer that also has highest efficiency.

2. MAXIMUM POWER TRANSFER AND MAXIMUM EFFICIENCY

Although it is well known that maximum power is transferred to a load impedance from a source when the source impedance and the load impedance are complex conjugates, this principle is useful in communication and instrumentation systems. For power systems, several researchers consider system energy efficiency also in addition to power transfer efficiency. For illustration, suppose a simple DC circuit shown in Figure 1(a) has E = 1 V, $R_s = 500\ \Omega$. As R_L is varied, we find that power transferred to the load P_L is maximum when $R_L = R_s$. We define the following characteristic parameters:

P_L	=	Power dissipated in the load resistance R_L
P_s	=	Power dissipated in the source resistance R_s
P_t	=	Power supplied by the voltage source E
P_{max}	=	Maximum value of P_s when $R_L = 0$
p_L	=	P_L / P_{max}
p_s	=	P_s / P_{max}
p_t	=	P_t / P_{max}
P^*_{max}	=	Maximum value of P_t when $R_L = R_s$
η_E	=	P_L / P_t
η_T	=	P_L / P^*_{max}

These are shown in Figure 1(b),(c). In the next section we shall deal with inductive power two coupled circuits, but also in case of multiple coupled circuits involving relay resonators.

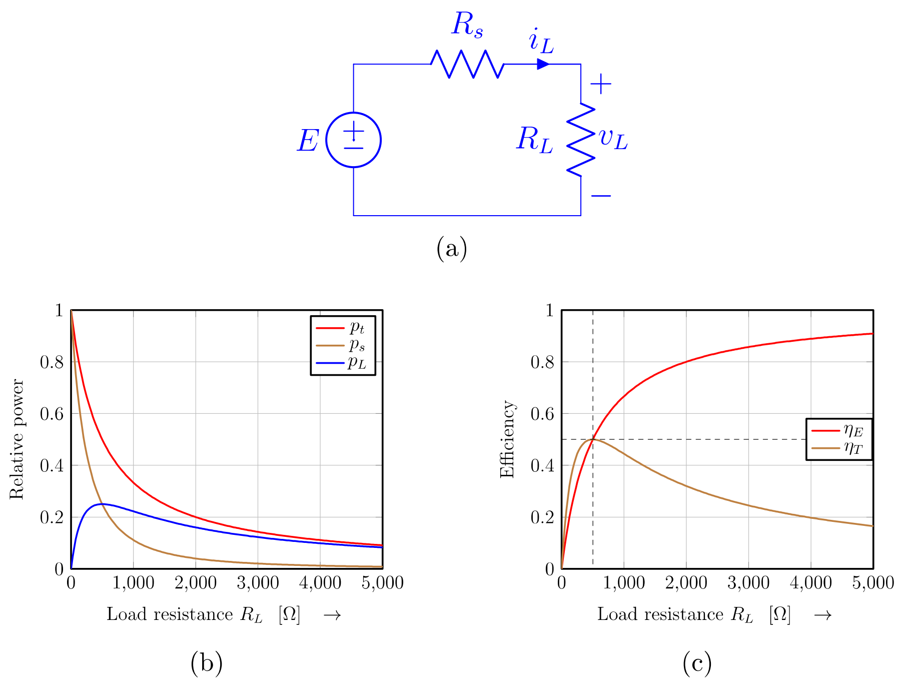

Figure 1 (a) A simple DC circuit with E = 1 V and R_s = 500 Ω. (b) Variation of p_t, p_s, and p_L as a function of R_L. (c) Variation of Power transfer efficiency and power system efficiency

3. INDUCTIVE POWER TRANSFER

The theory behind long-range power transfer is founded on the radiation mechanism of antennas. Accelerating charge is necessary for radiation to occur. In that connection one may start with the idea of "oscillating electric dipole," which is the building block of a transmit- ting antenna. This topic is not the focus of the present paper. But the underlying principle of mid-range WPT is simply inductive power transfer. Energy stored in the magnetic field is made to couple between two coils, one being the transmitting coil and the other being the receiving coil. For significant transfer of power it is necessary that both coils should have the same resonant frequency. The resonant pair of coils forms what is known as "oscillation transformer" Magnetic resonance is harnessed in the transfer of energy from one coil to the other.

The simple case of two coils may be extended to N multiple coils. Suppose one coil is excited with a power source, all the others could be made to receive power. Application of the Kirchhoff's voltage law (KVL) yields a system of mesh equations, which concisely can be written as:

$$\mathbf{Z}\,\mathbf{I} = \mathbf{V} \qquad (1)$$

where **Z** refers to the impedance matrix of size N × N, **I** is the vector of mesh currents and **V** is the vector of potential rises in each mesh. If the first mesh has the source voltage E and all others are passive, the kth element of the voltage vector is $V_k = E\delta(k - 1)$. If R_k, L_k, C_k are the resistance, inductance and capacitance seen in each mesh and if M_{mn} is the mutual inductance between the inductance in mth mesh and that in nth mesh, we can write

$$Z_{mn} = \begin{cases} R_m + j\left(\omega L_m - \frac{1}{\omega C_m}\right) & m = n < N \\ R_L + R_N + j\left(\omega L_N - \frac{1}{\omega C_N}\right) & m = n = N \\ j\omega M_{mn} & m \neq n \end{cases} \quad (2)$$

In the above, we assume that the N^{th} mesh has the load resistance R_L. Also, we can write $M_{mn} = \kappa_{mn}\sqrt{L_m L_n}$ where κ_{mn} is the coupling coefficient. Solving (1) we get the mesh currents. From the N^{th} mesh current which we can write as I_L we can get the load power as $P_L = |I_L|^2 R_L$.

Simulation Example: We will now perform a simulation example. Consider the circuit shown in Figure 2. The values used are $L_1 = L_3 = 104.3$, $L_2 = 62$ µH, $M_{12} = 63.884$ nH, $C_1 = C_2 = 1.98$ nF. The ohmic resistance of the coils is assumed as $R_1 = R_2 = 0.5$ Ω and the load resistance is chosen as $R_L = 1$ Ω. With $E = 1\angle 0^o$, the load power P_L is found over a band of frequencies and is plotted in Figure 4. Next by inserting a relay circuit we repeat the process. The values chosen for the circuit in Figure 3 are $L_1 = L_3 = 104.3$, $L_2 = 54$ µH, $M_{12} = 367.74$, $M_{13} = 63.884$, $M_{23} = -367.74$ nH, $C_1 = C_3 = 1.98$, $C_2 = 4.2$ nF. The ohmic resistance of the coils is assumed as $R_1 = R_2 = R_3 = 0.5$ Ω and the load resistance is chosen as $R_L = 1$ Ω. The load power P_L is again found over a band of frequencies and is plotted again in Figure 4. The P_L curves indicate that the three coil WPT system is superior to the two-coil counter part. From the figure we find that we achieved twice the power in the load. As for the system efficiency, we have not taken low values for the ohmic resistance of coils. Hence the actual value of efficiency is very less; however, it has increased from a 1.7% to 3.4%. But when the experiment is repeated with an ohmic resistance of 10 mΩ, it has increased from 65% to 80%. The middle coil acts as a relay coil. The analysis of WPT systems employing relay coils and additional circuits for optimizing the energy transfer are reported by several authors [15, 18]. The optimization problem has an exhaustive number of parameters to vary. The individual R, L, C elements in each circuit, mutual coupling between circuits, load resistance, impedance matching and so on come into play. The coupling is determined by the geometry of the coils and the distance between them. Not only the parameters, but also the constraints imposed by the practical issues and the target devices where WPT is intended would influence the solution to this problem. The overall goal is, to build these systems and replenish them as charging hotspots in all public places and make the electronic devices easy to use especially in mobile environments.

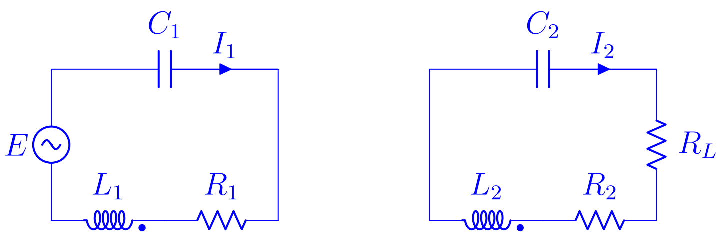

Figure 2 A two-coil WPT System

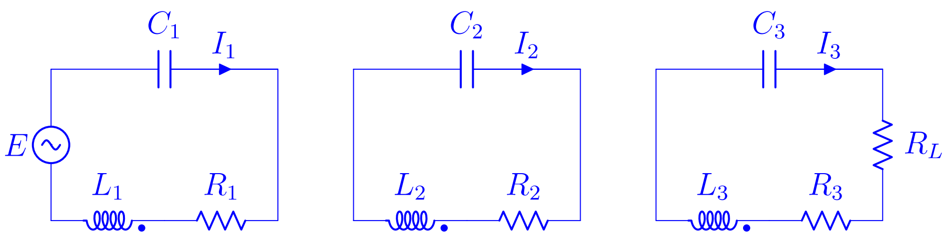

Figure 3 A three-coil WPT System

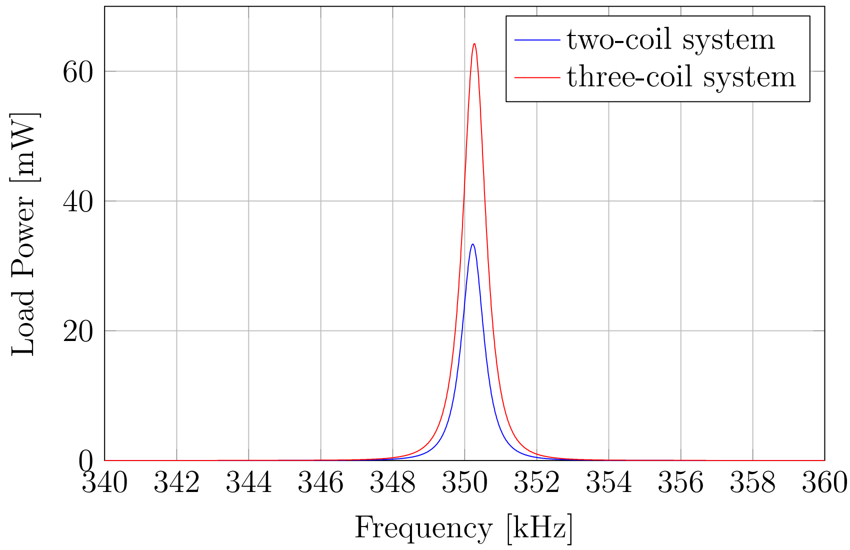

Figure 4 Load Power as a function of frequency

4. CONCLUSIONS

This paper reviewed the idea of WPT and the trends happening in its technology. We have seen how maximum power transfer theorem is more relevant in the communications and instrumentation scenarios, but maximum efficiency is equally important in power systems. Almost a century ago Tesla pioneered in the area of WPT. Due to lack of adequate infrastructure and device technology, he could not come up with a finished design. But more recently for the past decade, this field of research has witnessed renewed emphasis and the hardware is reaching commercialization. Also, standards are being developed, an example being Qi. As a consequence of the vast following, a consortium is formed and this technology is booming all over the world.

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BIOGRAPHICAL SKETCHES

SUDARSHAN R. NELATURY received his M.E. and Ph.D. from the Osmania University, Hyderabad, India in 1985 and 1996 respectively. From 1983 to 1999 he taught at the Electronics & Communications Engineering Department, Osmania University. From 1999 to 2003, he was a visiting faculty member at Villanova University, Villanova, PA. In the year 2003 he joined the School of Engineering, Penn State Erie, Erie PA, where he is currently an Associate Professor. During the Spring of 2012, while on Sabbatical, he was a visiting faculty at the School of Engineering and Applied Science, University of Pennsylvania, Philadelphia, PA. His interests are in Electromagnetics and Signal Processing. He authored over 100 professional papers and co-authored with Dr. Sadiku solution manuals and book chapters. His most recent publication is the graduate level textbook entitled, Analytical Techniques in Electromagnetics brought out by CRC Press, which he co-authored with Dr. Sadiku. He was the recipient of the Outstanding Research Award from the School of Engineering, and The Council of Fellows Research Award from Penn State Erie, The Behrend College in 2008. Dr. Nelatury is an alumnus of JNTU, Hyderabad, a member of Tau Beta Pi, a Life Member of India’s IETE and ISTE, and a Senior Member of IEEE.

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